Flared Disks and Silicate Emission in Young Brown Dwarfs

Subhanjoy Mohanty[1], Ray Jayawardhana[2], Antonella Natta[3],
Takuya Fujiyoshi[4], Motohide Tamura[5], David Barrado y Navascués[6]

ABSTRACT

We present mid-infrared photometry of three very young brown dwarfs located in the ρ Ophiuchi star-forming region – GY5, GY11 and GY310 – obtained with the Subaru 8-meter telescope. All three sources were detected at 8.6 and 11.7μm, confirming the presence of significant mid-infrared excess arising from optically thick dusty disks. The spectral energy distributions of both GY310 and GY11 exhibit strong evidence of flared disks; flat disks can be ruled out for these two brown dwarfs. The data for GY5 show large scatter, and are marginally consistent with both flared and flat configurations. Inner holes a few substellar radii in size are indicated in all three cases (and especially in GY11), in agreement with magnetospheric accretion models. Finally, our 9.7μm flux for GY310 implies silicate emission from small grains on the disk surface (though the data do not completely preclude larger grains with no silicate feature). Our results demonstrate that disks around young substellar objects are analogous to those girdling classical T Tauri stars, and exhibit a similar range of disk geometries and dust properties.

Subject headings: stars: low mass, brown dwarfs – stars: pre-main-sequence – circumstellar matter – planetary systems – stars: formation

1. Introduction

Now that a large number of brown dwarfs are known, some with inferred masses close to those of extrasolar giant planets, their origin has become a subject of widespread interest and

[1]Harvard-Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138, U.S.A. smohanty@cfa.harvard.edu

[2]Astronomy Department, University of Michigan, 830 Dennison Building, Ann Arbor, MI 48109, U.S.A.

[3]Osservatorio Astrofisico di Arcetri, INAF, Largo E. Fermi 5, I-50125 Firenze, Italy.

[4]Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, Hawaii.

[5]National Astronomical Observatory of Japan, Osawa 2-21-1, Mitaka, Tokyo 181-8588, Japan.

[6]Laboratorio de Astrofísica Espacial y Física Fundamental, INTA, P.O. Box 50727, E-2808 Madrid, Spain.

fundamental importance. One key recent finding is that substellar objects harbor accretion disks and undergo a T Tauri phase similar to that of low-mass stars, possibly suggesting a common formation mechanism. The evidence for disks around brown dwarfs includes near- and mid-infrared excess (e.g., Tamura et al. 1998; Natta & Testi 2001; Natta et al. 2002; Jayawardhana et al. 2003), spectroscopic signatures of accretion (e.g., Jayawardhana, Mohanty & Basri 2002, 2003; Muzerolle et al. 2003) and millimeter-wave emission (Klein et al. 2003). In some cases, these disks appear to last for up to 10 million years (Mohanty, Jayawardhana & Barrado y Navascués 2003), a timescale comparable to that of disks surrounding low-mass stars. Moreover, there are now indications of jets/outflows from objects close to or below the substellar limit (Fernández and Comerón 2001; Barrado y Navascués, Mohanty & Jayawardhana 2004), further strengthening the T Tauri analogy.

Given the much lower mass and intrinsic luminosity of brown dwarfs relative to T Tauri stars, the preceding discoveries raise intriguing questions about how the detailed properties of brown dwarf disks compare to those of T Tauri disks. Observations in the mid-infrared, where optically thick disk emission dominates over the substellar photosphere, can provide important constraints on the disk models. Here we report ground-based photometry in the 8.6, 9.7 and 11.7μm filters, spanning the 10μm silicate feature, of three young brown dwarfs in the nearby ρ Ophiuchi region (age$\lesssim$1 Myr, d$\approx$150 pc), and use these data to explore their disk characteristics in comparison with models.

2. Observations and Data Reduction

All our photometry was obtained with the Cooled Mid-Infrared Camera and Spectrograph (COMICS; Okamoto et al. 2003) on the Subaru telescope, on Mauna Kea. In imaging mode, the instrument offers a $42'' \times 32''$ field of view, with a plate scale of $0.13''$/pixel (diffraction-limited seeing at $\sim$10μm is $0.31''$, or $\sim$2pix); we observed under seeing conditions of $1''$or better. We acquired data through 3 filters: a narrow-band filter centered on 8.6μm (width $\approx$ 0.4μm), and two broad-band filters centered on 9.7 and 11.7μm (widths $\approx$ 1μm). [GY92]5 (ISO-Oph 30) and [GY92]310 (ISO-Oph 164) were observed on 2003 June 18 UT; [GY92]11 (ISO-Oph 33) was observed on 2003 July 16 UT. The flux standards HR5013 and HD152880 were also observed on the former night, and HD152880 alone on the latter. Data were obtained in standard chop-and-nod mode for science targets and calibrators. Time constraints only allowed observations at 8.6 and 11.7μm for GY11, and not at 9.7μm; the other two ρ Oph sources were observed in all three filters. Typical integration times were $\sim$1200s per filter for the science targets.

Aperture photometry was performed on the dark-subtracted, flat-fielded and coadded

final images, using the *apphot* package in *IRAF*[7]. Our final errors are $\lesssim$ 0.05 mag in calibration for HR5013 and HD152880, and ∼0.15 mag in aperture photometry for GY5 and GY310, resulting in a total error of ∼15% in the inferred flux in all filters for the latter two objects. For the faintest source GY11, we conservatively estimate an uncertainty of ∼0.25 mag in our photometry, yielding a final flux error of ∼25% at both 8.6 and 11.7μm.

GY5 is observed but not detected at 9.7μm, in either the individual nod frames or in the coadded frames at a single nod position. Under the circumstances, we derive a 3σ detection upper limit of 35 mJy from the individual frames. This value is consistent with our detected 9.7μm flux of ∼35 mJy in GY310, observed for nearly the same length of time: the latter source is just visible at the 2–3σ level in the individual nod frames (but clearly detected at ∼6σ in the co-added frames). Our Subaru fluxes are listed in Table 1. In our analysis of the spectral energy distributions (SEDs), we have also included the ISO 6.7 and 14.3 μm fluxes derived for these sources by Bontemps et al. (2001) with an angular resolution of 6 arcsec, and the ISO 3.6, 4.5 and 6.0 μm fluxes for GY5 and 11 from Comeron et al. (1998) with 3-arcsec resolution; these all have errors $\geq$ 10%.

3. Stellar Parameters

We are interested here in the luminosity, mass and radius of our targets. Mass is pertinent for establishing whether these are bona-fide brown dwarfs, while luminosity and (to a lesser extent) mass and radius are important for modelling their disk properties (§4). Our stellar parameters for GY5, 11 and 310 are adopted from Natta et al. (2002, hereafter NTC02); the reader is referred to that work for a detailed discussion of the methodology. The derived quantities are listed in Table 1. NTC02 estimate errors of ±100K in T_{eff} , 20–30% in L_{bol} , and 20–30% in mass (the L_{bol} errors derive mainly from those in A_V , and are likely somewhat higher in the faintest, heavily reddened objects; see discussion of GY11 in §5). They find a spectral type of M6, T_{eff} of 2700K and mass of 60±20 M_J for both GY5 and 310, and M8.5, 2400K and 10±2 M_J for GY11. The inferred bolometric luminosities for GY5 and 310 are very similar, 0.07 and 0.09 $L_\odot$ respectively; GY11 appears much less luminous at ∼0.008 $L_\odot$. These values put all three bodies below the brown dwarf boundary at ∼80 M_J ; indeed, GY11 seems to lie close to the deuterium-burning limit of ∼12 M_J (as also argued by Testi et al. 2002).

For comparison, we note that Luhman & Rieke (1999; hereafter LR99) have also inves-

[7] *IRAF* is distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation, USA.

tigated the properties of ρ Oph members, using K-band spectra and an analysis technique differing from that of NTC02. For GY310, their inferred L_{bol} and T_{eff}, and hence mass from theoretical tracks, are almost exactly those derived by NTC02. The brown dwarf status of this object thus seems secure. For GY5, their T_{eff} and L_{bol} (2900K and 0.11 $L_\odot$) are slightly higher than NTC02's values, implying a somewhat larger mass of $\sim$ 80 M_J. We cannot be confident therefore that this is a bona-fide brown dwarf; nevertheless, this higher mass estimate still implies an object very close to the substellar boundary. Moreover, using LR99's estimates does not significantly alter our disk models for this object or affect our conclusions regarding its disk properties.

The situation is somewhat more complicated for GY11. LR99 find this object to be simultaneously much hotter ($T_{eff} \sim$ 2800K) and fainter ($L_{bol} \sim$ 0.003 $L_\odot$) than NTC02 derive. Results similar to LR99's are obtained by Wilking, Greene & Meyer (1999; hereafter WGM99) as well; like LR99, WGM99 also employ K-band spectra. Theoretical evolutionary tracks (e.g., D'Antona & Mazzitelli 1997; Chabrier et al. 2000) then imply a substantially higher mass, 30–40 M_J, than NTC02's value. However, they also then imply an age of $\sim$10 Myr (see comparisons to evolutionary tracks in LR99 and WGM99). Now, the infrared excess and veiling of GY11, signifying large amounts of circum-(sub)stellar material, confirm it to be a true member of the young ρ Oph star-forming region (WGM99), which has an estimated age $\lesssim$ 1 Myr. Thus, the LR99 (and WGM99) values for GY11 appear suspect. As WGM99 point out, it is quite possible that veiling by dust causes its T_{eff} from a K-band analysis to be significantly overestimated. Moreover, the H_2O bands used by LR99 and WMG99 possibly saturate with later M type, which can also result in a spuriously high T_{eff} determination (LR99). Spectral type and T_{eff} errors will lead to erroneous inferred luminosity as well. The estimates by NTC02 are less susceptible to these particular uncertainties: their J- and H-band analysis of the overall spectral shape depends less on H_2O band-strengths alone, and is plausibly less affected by excess emission from dusty disks than K-band studies. These considerations, and the fact that NTC02's luminosity and T_{eff} are in fact consistent with an age $\lesssim$ 1 Myr, suggest that the NTC02 parameters we adopt for GY11 are more reasonable and appropriate. In any case, even the higher T_{eff} of LR99 implies a substellar mass for this object, whether one adopts their L_{bol} or the NTC02 value ($\sim$ 40 M_J in both cases; also see §5).

4. Disk Models

To investigate the disk SEDs of our targets, we employ passive disk models that only consider the effect of reprocessed stellar irradiation and ignore viscous accretion heating;

this is justified for the very low accretion rates, $\sim 10^{-9}$–10^{-12} $M_\odot$ yr^{-1}, inferred so far in the substellar regime (Muzerolle et al. 2003). Our models are based on the 2-layer description of Chiang and Goldreich (1997; hereafter CG97) as modified by Dullemond et al. (2001); scattering is included in an approximate fashion, following Dullemond & Natta (2003). The disk geometry is assumed to be either flared or flat. In the former case, consistent with hydrostatic equilibrium for well-mixed gas and dust (Kenyon & Hartmann 1987), the vertical temperature structure at any radius is described by two components: the temperature in the interior of the disk and that at the disk surface, which is an optically thin layer directly exposed to stellar radiation. The flat, geometrically thin case is modelled simply as an optically thick blackbody disk which has no silicate emission. This situation may correspond to complete settling of large grains to the disk midplane (e.g., D'Alessio et al. 2001). We assume a distance of 150pc to the ρ Oph region, consistent with the latest estimate by de Zeeuw et al. (1999).

The disks are scaled-down version of typical T Tauri disks; detailed parameters are given in NTC02 (see also Fig.1 caption). The gas and dust are assumed to be well-mixed in the flared models. As discussed in NTC02, the emission in the near- and mid-IR depends only on a few disk parameters, namely the disk inclination and inner radius and the properties of grains on the disk surface, for which we adopt a mixture of graphite (containg 30% of the cosmic C abundance) and astronomical silicates (containg all cosmic Si abundance) with grain radius a. Two distinct particle distributions are examined: *(i)* $a_{min} = 0.2\mu$m and $a_{max} = 3.6\mu$m; and *(ii)* a_{min}=3μm and a_{max}=12μm. In both cases, the size distribution goes as dn/d$a \propto$ a$^{-3.5}$. The two situations allow us to explore the effect of grain growth on the SEDs. For the calculations presented here, the surface grains properties are not crucial as long as a remains smaller than a few microns. As for stellar parameters, the most important one is L_{bol} ; for flared disks, there is also a weak dependence of the flaring angle on the stellar mass and radius (CG97).

5. Results and Discussion

SED model fits to our data for GY310, 11 and 5 are illustrated in Fig. 1. We plot both our new Subaru data at 8.6, 9.7 and 11.7μm as well as additional flux measurements at shorter and longer wavelengths, mainly from ISO. The flux-calibrated near-infrared (0.85–2.45μm) stellar spectra from NTC02 are also shown. All the observed fluxes have been corrected for reddening following NTC02. For each object, we plot two flared disk models, one with a distribution of small grains and the other with larger grains; a flat disk (blackbody) model; and a model stellar spectrum (Allard et al. 2001; see NTC02) depicting the contribution

of the underlying stellar photosphere. The models incorporate inner holes of various sizes. The effect of an inner hole in a flared disk is twofold. On the one hand, it depresses the near-IR emission, by getting rid of the innermost hot dust; on the other hand, it increases the fraction of the stellar surface "seen" by the disk (from 1/2 to 1, in the extreme cases $R_i = R_*$ (no hole) and $R_i \gg R_*$ respectively), and therefore the emission at longer wavelengths. All three targets exhibit considerable mid-IR excess above the stellar continuum: while their earlier ISO detections left open the possibility of source confusion due to ISO's coarse spatial resolution, the Subaru detections confirm that these objects harbor circum-(sub)stellar disks. The salient results from our present work are as follows: *(1)* both GY310 and GY11 clearly possess flared disks - flat disks can be confidently ruled out in their case, *(2)* the 9.7μm flux for GY310 indicates possible silicate emission from small surface grains (though larger grains with no silicate emission cannot be completely excluded), and *(3)* inner holes of size $\sim$ 3–7 stellar radii seem necessary to fit the data, analogous to the situation in classical T Tauri stars. We now briefly discuss each source.

GY 310: Our best fit for this object requires a flared disk, tilted 60° from face-on and with an inner-hole radius of $R_i \approx 7R_*$. Inner holes significantly smaller than this produce too much emission at 6.7μm, while smaller inclinations overestimate the mid-IR flux. Notice that a flat disk model is completely inconsistent with the data longward of 6.7μm; the predicted fluxes are simply too low. Moreover, all the fluxes from 6.7 to 14.3 μm agree remarkably well with the flared disk SED that includes 10μm silicate emission from small surface grains. A silicate feature is routinely observed in disks around T Tauri stars (e.g., Cohen & Witteborn 1985; Natta, Meyer & Beckwith 2000). If our detection is confirmed, it would be the first evidence of such emission from a brown dwarf disk. Nevertheless, we caution that our present data cannot unequivocally rule out a flared disk with larger grains and no silicate feature: our 9.7μm flux remains marginally consistent with the latter scenario. Measurements with smaller uncertainties, such as Spitzer low-resolution spectra, can settle this issue conclusively.

GY 11: Our best-fit model for this brown dwarf is a flared disk seen face-on, with an inner hole of size $R_i \approx 3R_*$. Much smaller inner holes produce unacceptably low mid-IR fluxes. Similarly, a flat disk produces emission wholly inadequate to match the steeply rising mid-IR SED. However, in the absence of 9.7μm data, we are not sensitive to the presence of 10μm silicate emission, and thus cannot distinguish between flared disks with small surface grains and those with somewhat larger particles. We note that the L_{bol} we adopt for GY11 (0.012 $L_\odot$), to obtain an adequate SED fit, is moderately higher than derived by NTC02 (0.008 $L_\odot$). The NTC02 value produces mid-IR fluxes somewhat lower than observed (fit not shown); since we already maximize the mid-IR emission by adopting a face-on disk and invoking an inner hole$\sim$ $3R_*$, higher luminosity seems the only remaining option in the context of our models. The L_{bol} adopted here is admissible within NTC02's A_V errors

for this heavily reddened object (our L_{bol} amounts to $A_V \approx 8.5$ instead of NTC02's 7.5 ± 1). The T_{eff} from synthetic spectral fits assuming our new A_V is 2500K, very close to NTC02's 2400K; the new L_{bol} and T_{eff} also remain consistent with an age $\lesssim$ 1 Myr. The mass now inferred from the evolutionary tracks is $\sim$ 20 M_J ; while higher than NTC02's estimate of 10 M_J , it still implies that GY11 is a very low-mass brown dwarf.

GY 5: The large scatter in the GY 5 data make any fit provisional at best. However, if we disregard the ISO 3.6μm flux, which is 50% larger than the ground-based value in the comparable L' filter (from Comeron et al. 1998 and Jayawardhana et al. 2003) and assume that the true fluxes at 6.7 and 14.3μm are at the lower end permissible by the ISO error bars, then a flat disk inclined at $\sim 65°$ to face-on, with an inner hole $R_i \sim 5R_*$, provides a plausible fit (especially since our 9.7μm Subaru estimate is only a flux upper limit). However, we cannot discount a flared disk seen at large inclination.

The disk parameters presented here for the three ρ Oph sources are not unique: there are plenty of trade-offs between factors such as disk inclination, inner-hole size, grain albedos and sizes, and degree of dust settling. For example, our models adopt only the two extremes of grain settling: well-mixed gas and dust leading to full disk flaring and complete settling resulting in flat disks. If there is some, but not complete, dust settling in GY310 for instance, its moderate mid-IR excess may be fit by a disk model with a lower inclination.

Nonetheless, the SEDs we observe strongly suggest certain qualitative features that are relatively independent of the particular disk parameters adopted. First, the presence of flared disks in GY310 and 11 is indubitable: no flat disk, whatever its inner-hole radius or inclination, can reproduce the observed increase in their flux from 6.7 to 14.3 μm. Apai et al. (2002) carried out observations similar to ours for a single young object at the stellar/substellar edge, ChaHα2, and found that a flat disk with no silicate feature provides the best fit to its SED. Our results indicate that, while such disks might indeed be present in some cases (e.g., perhaps GY5), this does not signify a fundamental change in disk properties upon crossing from the stellar to the substellar regime: brown dwarfs can have flared disks too, as well as (tentatively) silicate emission, and simply present a range of disk geometries just as T Tauri stars do (e.g., Miyake & Nakagawa 1995). Second, inner holes of a few substellar radii may be common in brown dwarf disks - our best fits to all three objects require such a configuration. Especially for GY11, it is hard to find an alternative; even assuming a face-on disk and a (sub)stellar luminosity higher than previously estimated, some mechanism is required to further raise the mid-IR fluxes to match the data, and a central hole seems the only viable possibility (see also Liu et al. 2003). Indeed, magnetospheric accretion models predict the formation of inner holes of just these sizes in both classical T Tauri stars and accreting brown dwarfs, due to disk truncation by interaction with the (sub)stellar magnetic

field (Shu et al. 1994; Muzerolle et al. 2003). In summary, therefore, our study suggests that brown dwarf disk properties are qualitatively similar to those of higher mass T Tauri stars. A more detailed understanding of grain characteristics, dust settling and geometry in brown dwarf disks will be possible with mid-IR Spitzer observations.

We thank the Subaru staff for outstanding support, and Karl Haisch Jr. for advice on IR reductions. SM gratefully acknowledges support from the SIM-YSO grant. This work was supported in part by NSF grant AST-0205130 to RJ. AN acknowledges support from the MIUR grant "*Low-mass stars and brown dwarfs*". MT acknowledges support by Grant-in-Aid (12309010). DByN is indebted to the Spanish "Programa Ramón y Cajal" and AYA2003-05355. We thank the referees, Ilaria Pascucci and Daniel Apai, for a prompt and very helpful review.

REFERENCES

Allard,F., Hauschildt,P., Alexander,D., Tamanai,A., Schweitzer,A., 2001, ApJ, 556, 357

Apai,D., Pascucci,I., Henning,Th., Sterzik,M., Klein,R., Semenov,D., Güenther,E., Stecklum,B., 2002, ApJ, 573, L115

Barrado y Navascués, D., Mohanty,S. & Jayawardhana,R., 2004, ApJ, 604, 284

Beckwith,S., Sargent,A., Chini,R., Guesten,R., 1990, AJ, 99, 924

Bontemps,S., André,P., Kaas,A. et al., 2001, A&A, 372, 173

Chabrier,G., Baraffe,I., Allard,F., Hauschildt,P., 2000, ApJ, 542, 464

Chiang,E. & Goldreich,P., 1997, ApJ, 490, 368 [CG97]

Cohen,M. & Witteborn,F., 1985, ApJ, 294, 345

Comeron,F., Rieke,G., Claes,P., Torra,J., Laureijs,R., 1998, A&A, 335, 522

D'Alessio,P., Calvet,N. & Hartmann,L., 2001, ApJ, 553, 321

D'Antona,F., & Mazzitelli,I., 1997, *Memorie della Societá Astronomica Italiana*, 68, 807

de Zeeuw,P., Hoogerwerf,R., de Bruijne,J., Brown,A., Blaauw,A., 1999, AJ, 117, 354

Dullemond, C.P., Domink, C., Natta, A., 2001, ApJ, 560, 957

Dullemond, C.P., & Natta, A., 2003, A&A, 405, 597

Fernández,M. & Comerón,F., 2001, A&A, 380, 264

Jayawardhana,R., Mohanty,S. & Basri,G., 2002, ApJ, 578, L141

Jayawardhana,R., Mohanty,S. & Basri,G., 2003, ApJ, 592, 282

Jayawardhana,R., Ardila,D., Stelzer,B. & Haisch,K.E.Jr., 2003, AJ, 126, 1515

Kenyon,S. & Hartmann,L., 1987, ApJ, 323, 714

Klein,R., Apai,D., Pascucci,I., Henning,Th., Water,L., 2003, ApJ, 593, L57

Liu,M., Najita,J. & Tokunaga,A., 2003, ApJ, 585, 372

Luhman,K. & Rieke,G., 1999, ApJ, 525, 440 [LR99]

Miyake,K. & Nakagawa,Y., 1995, ApJ, 441, 361

Mohanty,S., Jayawardhana,R. & Barrado y Navascués,D., 2003, ApJ, 593, L109

Muench,A., Alves,J., Lada,C., Lada,E., 2001, ApJ, 558, L51

Muzzerolle,J., Hillenbrand,L., Calvet,N., Briceño,C., Hartmann,L., 2003, ApJ, 592, 266

Natta, A., Meyer,M. & Beckwith,S., 2000, ApJ, 534, 838

Natta, A. & Testi,L., 2001, A&A, 376, L22

Natta, A., Testi, L., Comerón, F., Oliva, E., D'Antona, F., Baffa, C., Comoretto, G., Gennari, S., 2002, A&A, 393, 597 [NTC02]

Okamoto,Y.K., Kataza,H., Yamashita,T., Miyata,T., Sako,S., Takubo,S., Honda,M., Onaka,T., 2003, *Proceedings of the SPIE*, ed. Iye,M. & Moorwood,A., 4841, 169

Shu,F., Najita,J., Ostriker,E., Wilkin,F., 1994, ApJ, 429, 781

Tamura,M., Itoh,Y., Oasa,Y., Nkajima,T., 1998, Science, 282, 1095

Testi,L., Natta,A., Oliva,E., D'Antona,F., Comeron,F., Baffa,C., Comoretto,G., Gennari,S., 2002, ApJ, 571, L155

Wilking,B., Greene,T. & Meyer,M., 1999, AJ, 117, 469 [WGM99]

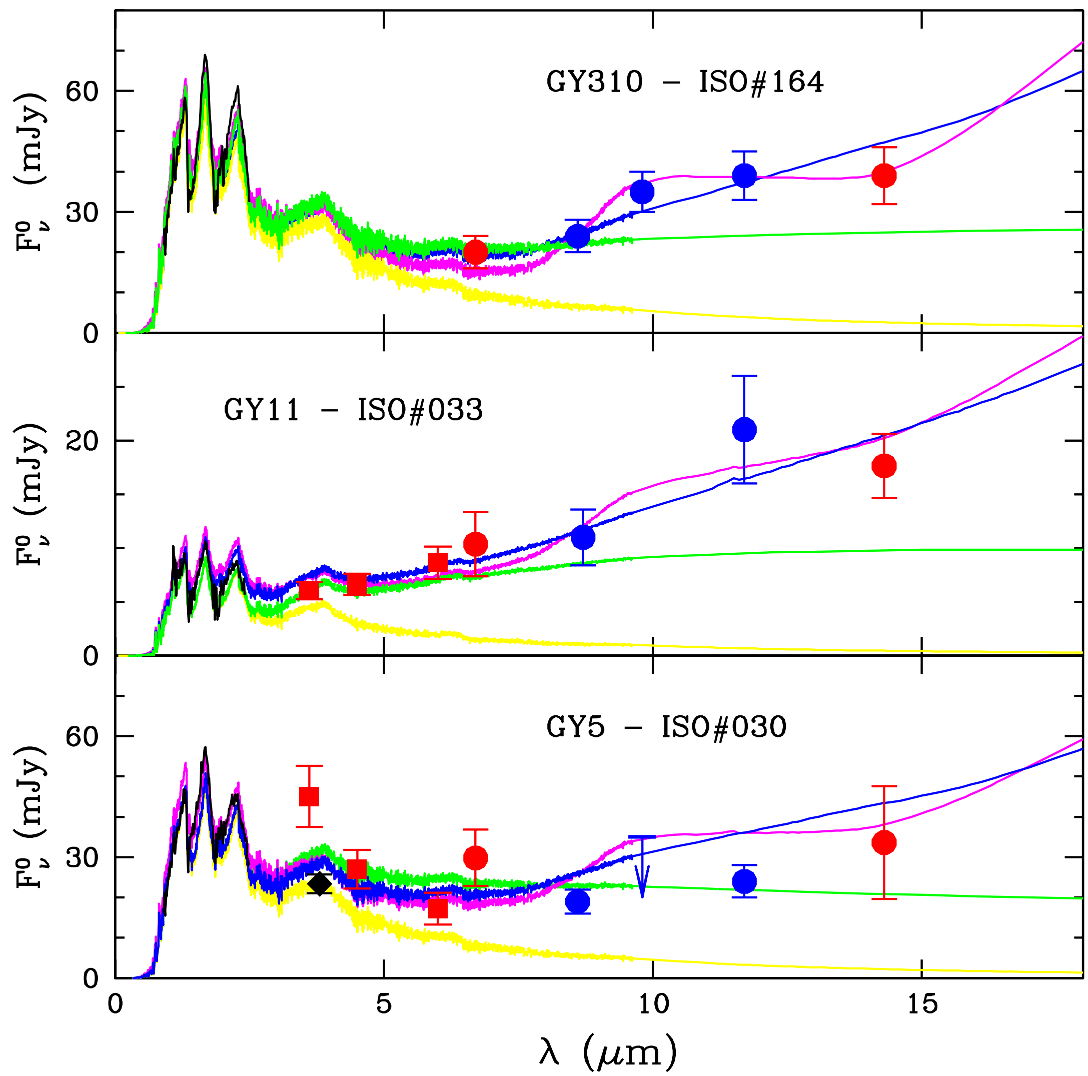

Fig. 1.— *Top panel*: Observed fluxes and model predictions for GY310 (ISO#164). Blue dots from this paper, red dots from Bontemps et al. (2000); black curve shows the near-IR low-resolution spectrum from NTC02. All observations are corrected for reddening (A_V =6 mag; NTC02). The magenta curve shows the prediction of a star + flared disk model with small grains; the blue curve a star + flared disk with large grains; the green curve is the

---

This preprint was prepared with the AAS LATEX macros v5.0.

SED of a flat blackbody disk. The photospheric flux for the adopted substellar parameters is in yellow. The flared disks have $R_i \sim 7R_*$, inclination of 60°. The flat disk has $R_i \sim 5R_*$, same inclination. *Middle Panel*: Same for GY11 (ISO#033). The red squares are ISO fluxes from Comerón et al. (1998). The adopted stellar parameters (see §5) are L_{bol} =0.012$L_\odot$, A_V =8.5 mag. All disks have $R_i \sim 3R_*$ and are seen face-on. *Bottom Panel*: Same for GY5 (ISO#030). The black diamond is an L′ flux ground-based measurement from Comerón et al. (1998). The flared disks have $R_i \sim 5R_*$, inclination $\sim 60°$. The flat disk has $R_i \sim 5R_*$ and inclination $\sim 65°$. For all 3 objects, the other disk parameters are: disk outer radius of $R_D = 1{\times}10^{15}$ cm (67 AU); disk mass of $M_D = 0.03\ M_*$; disk surface density profile $\Sigma \propto R^{-1}$. The dust in the disk interior is assumed to have an opacity $\kappa = 0.01(\lambda/1.3\ \mathrm{mm})^{-1}\ \mathrm{cm^2 g^{-1}}$ (Beckwith et al. 1990). Overall results in this figure do not depend on the exact values of these parameters.

Table 1. Stellar Parameters and Mid-Infrared Fluxes

name	SpT[a]	T_{eff} [a] (K)	L_{bol} [a] ($L_\odot$)	M[a] (M_J)	A_V [a] (mag)	6.7μm[b] (mJy)	8.6μm[c] (mJy)	9.7μm[c] (mJy)	11.7μm[c] (mJy)	14.3μm[b] (mJy)
GY5	M6	2700	0.07	60	3.0	28±7	19±3	<35	24±4	33±14
GY11	M8.5	2400	0.008	10	7.0	9±3	11±3	–	21±5	17±3
	...	2500	0.012	20	8.5	...	...	...	...	...
GY310	M6	2700	0.09	60	6.0	20±2	24±4	35±5	39±6	39±6

[a]Spectral type, T_{eff} , L_{bol} , mass and A_V from NTC02. For GY11, we also provide, in the second row, the moderately different parameters suggested by our SED fits.

[b]6.7 and 14.3μm ISO fluxes from Bontemps et al. (2001).

[c]8.6, 9.7 and 11.7 μm fluxes observed by us at Subaru.